Suppression of extraneous thermal noise in cavity optomechanics

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Abstract: Extraneous thermal motion can limit displacement sensitivity and radiation pressure effects, such as optical cooling, in a cavity-optomechanical system. Here we present an active noise suppression scheme and its experimental implementation.

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1. Introduction

The field of cavity opto-mechanics has experienced remarkable progress in recent years [1] and it is now possible to realize ground state cooling. Reasons why only a few systems have successfully reached the quantum regime [2] relate to additional fundamental as well as technical sources of noise.

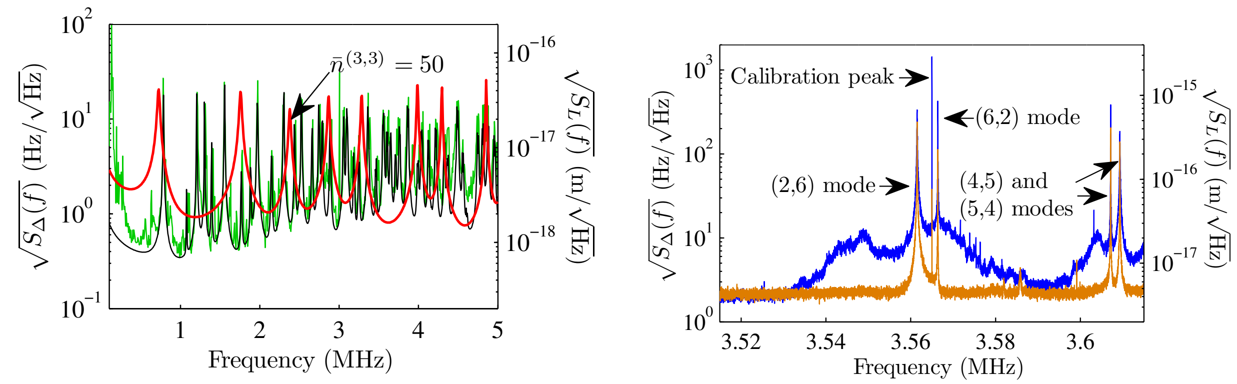
Here we address an ubiquitous source of extraneous noise: thermal motion of the cavity apparatus (including substrate and supports), which can dominate in systems operating at room temperature. Thermal noise is well understood to pose a fundamental limit on mechanics-based measurements spanning a broad spectrum of applications. In a cavity optomechanical system, *extraneous* thermal motion of the apparatus (i.e., structural vibrations *other than* the mode under study) gives rise to fluctuations of the cavity resonance frequency. Like laser frequency noise [5], these extraneous fluctuations can lead to noise heating as well as limit the precision of displacement measurement.

To combat this challenge, we propose and experimentally demonstrate a novel technique to actively suppress extraneous thermal noise in a cavity opto-mechanical system. A crucial requirement in this setting is the ability to sense and differentiate extraneous noise from intrinsic fluctuations produced by the oscillator's motion. To accomplish this, our strategy is to monitor the resonance frequencies of multiple spatial modes of the cavity, each with different sensitivity to the oscillator's motion but comparable sensitivity to extraneous thermal motion. This information can be used to electro-optically imprint "anti-noise" onto the frequency of the incident laser field, resulting in suppression of noise on the instantaneous cavity-laser detuning.

2. Experiment

Our experimental system is the same as reported in [3]. It consists of a high-Q nano-mechanical membrane coupled to a Fabry-Pérot cavity (using the techniques pioneered in [4]). Owing to the small length ($\langle L\rangle \simeq 0.74$ mm) and mode waist ($w_0 \simeq 33\,\mu$m) of our cavity, thermal motion of the end-mirror substrates gives rise to large fluctuations of the cavity resonance frequency ν_c. To measure this "substrate noise", we monitor the detuning Δ between a stable input field ("science field", coupled to TEM_{00} cavity mode) and the cavity with membrane removed. Plots of one-sided power spectral densities of detuning fluctuations $S_\Delta(f)$ are shown in Fig. 1(a). We also express the noise as "effective cavity length" fluctuations $S_L(f) = (\langle L\rangle/\langle\nu_c\rangle)^2 S_\Delta(f)$. The measured noise (green) is consistent with the noise predicted from a finite element model shown in black. We show a numerical model of the thermal noise produced by an optically damped membrane with thermal phonon occupation number for (3,3) membrane mode $\bar{n}^{(3,3)} = 50$. The magnitude of the membrane noise (red) would be commensurate with the noise produced by substrate thermal motion (green and black). Substrate thermal motion therefore constitutes an important a roadblock to observing quantum behavior in our system [3].

To implement the noise suppression scheme mentioned in the previous section, we monitor the detuning fluctuations of an other incident field ("probe field") coupled to TEM_{01} cavity mode, and electro-optically imprint it onto the frequency of the science field, with gain set so that this added "anti-noise" cancels the extraneous thermal fluctuations on the science field detuning. We measured the detuning fluctuations $S_\Delta(f)$ of the science field near $f_m^{(2,6)} \simeq 3.56$ MHz, the frequency of the (2,6) membrane mode. The magnitudes of $S_\Delta(f)$ with feedback noise suppression on (orange) and



(a) Spectra of detuning fluctuations $\sqrt{S_\Delta(f)}$ (also expressed as effective cavity length noise $\sqrt{S_L(f)}$) for our cavity. The observed noise (green) arises from substrate thermal motion, in agreement with the finite element model (black). Detuning noise due to membrane motion (red) with the (3,3) mode optically damped to a thermal phonon occupation number of $\bar{n}^{(3,3)} = 50$ is shown for comparison.

(b) Experimental substrate noise suppression for the science field. Orange and blue traces correspond to the spectrum of science field detuning fluctuations with and without feedback noise suppression, respectively. The feedback gain is fine-tuned by suppressing the detuning noise from a common FM tone at 3.565 MHz.

Fig. 1. Substrate thermal noise suppression for the science field in our cavity optomechanical system.

off (blue) are shown in Fig. 1(b). Comparing the two traces near 3.56 MHz in Fig. 1(b), we infer that the extraneous thermal fluctuations of the mirror substrates (broad blue structures) near $f_m^{(2,6)}$ is suppressed by a factor of 16, while the fluctuations from the (2,6) membrane mode itself (inferred from integrated areas below the two traces near $f_m^{(2,6)}$) is only suppressed by a factor of 3, in power. The substrate noise suppression in our system is limited by the shot noise of the probe field measurement. Further analysis suggests that the cooling limit of our system is reduced by $\sim$38% with the noise suppression [5].

The key point is to suppress extraneous detuning fluctuations without substantially reducing the fluctuations from the membrane motion. Such "differential suppression" is possible in our system because TEM_{00} and TEM_{01} cavity modes have nearly equal sensitivities to substrate thermal motion but different sensitivities to the membrane motion.

3. Conclusion

We have proposed and experimentally demonstrated a technique to suppress extraneous thermal noise in a cavity optomechanical system. Our technique involves mapping a measurement of the extraneous noise onto the frequency of the incident laser field to stabilize the associated laser-cavity detuning. In our system, we have shown that the end-mirror substrate thermal motion gives rise to large laser-cavity detuning noise. These extraneous detuning fluctuations are measured with multiple cavity spatial modes. In conjunction with feedback, the extraneous detuning fluctuations are suppressed without substantially reducing the fluctuations from the membrane motion. The authors gratefully thank Peter Rabl, Jun Ye, and Peter Zoller for inspiring discussions.

References

1. T. J. Kippenberg and K. J. Vahala, Opt. Express **15**, 17172 (2007).
2. See, e.g., A. O'Connell et al., Nature **464**, 697 (2010); J. Chan et al., Nature **478**, 89 (2011).
3. D. J. Wilson, C. A. Regal, S. B. Papp, and H. J. Kimble, Phys. Rev. Lett. **103**, 207204 (2009).
4. J. D. Thompson et al., Nature **452**, 72 (2008).
5. P. Rabl, C. Genes, K. Hammerer, and M. Aspelmeyer, Phys. Rev. A **80**, 063819 (2009).